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Twenty years of tillage research in subarctic Alaska I. Impact on soil strength, aggregation, roughness, and residue cover

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Abstract

Soil properties and surface characteristics affecting wind erosion can be manipulated through tillage and crop residue management. Little information exists, however, that describes the impact of long term tillage and residue management on soil properties in the subarctic region of the United States. This study examines the impact of 20 years of tillage and residue management on a broad range of physical properties that govern wind erosion processes on a silt loam in interior Alaska. A strip plot experimental design was established in 1983 and included intensive tillage (autumn and spring disk), spring disk, autumn chisel plow, and no tillage with straw either retained on or removed from the soil surface. Soil and residue properties measured after sowing barley (*Hordeum vulgare* L.) in May 2004 included penetration resistance, soil water content, shear stress, bulk density, random roughness, aggregate size distribution, and residue cover and biomass. No tillage was characterized by larger aggregates, greater soil strength (penetration resistance and shear stress), wetter soil, and greater residue cover compared to all other tillage treatments. Despite crop failures the previous 2 years, crop residue management influenced residue biomass and cover, but not soil properties. Autumn chisel and spring disk appeared to be viable minimum tillage options to intensive tillage in controlling erosion. Autumn chisel and spring disk promoted greater roughness, aggregation, and residue cover as compared with intensive tillage. Although no tillage appeared to be the most effective management strategy for mitigating wind erosion, no tillage was not a sustainable practice due to lack of weed control. No tillage also resulted in the formation of an organic layer on the soil surface over the past 20 years, which has important ramifications for long term crop production in the subarctic where the mean annual temperature is <0 °C.

Keywords: Wind erosion; Residue management; Soil stability; Soil erosion

1. Introduction

Preservation of soil resources is paramount for maintaining an adequate supply of food and fiber as well as preserving water and air quality for future generations. Indeed, water and air resources adjacent to agricultural lands are most likely to be impacted by loss of soil due to wind and water erosion. Conservation tillage practices reduce the exposure of the soil surface to the forces of wind and water and can therefore minimize the adverse effects associated with loss of top soil.

Tillage and crop residue management can influence soil physical properties as a direct result of altering the soil physical matrix or indirectly by altering surface energy partitioning, microbial activity, and soil chemical composition. Studies conducted in temperate

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regions suggest that soils are wetter (Willis and Bond, 1971; Arshad et al., 1995), denser (Izaurralde et al., 1986; Hill, 1990), and more stable (Singh et al., 1994) when subject to conservation tillage rather than conventional tillage practices. Some soil properties appear to have little or no response to straw management, including penetration resistance (Unger, 1984), hydraulic conductivity, and bulk density (Skidmore et al., 1986; Gupta et al., 1987). Maintenance of straw rather than removal from the soil surface, however, appears to enhance soil stability (Black, 1973; Smika and Greb, 1975) and wetness (Aase and Tanaka, 1987).

In Alaska, small grains are mainly grown in the interior region along the Tanana River Valley. Agricultural lands in interior Alaska are generally characterized by soils that are moderately to severely susceptible to wind erosion (Knight et al., 1979; Siddoway et al., 1984). An experiment was initiated by the University of Alaska-Fairbanks and USDA Agricultural Research Service in the early 1980s to develop conservation practices that would preserve soil resources in the interior region. The investigation focused on the impact of tillage and crop residue management practices on small grain production (Siddoway et al., 1984). In addition to grain production, other aspects of conservation tillage were also examined as part of this investigation. For example, Sharratt (1998) found that barley utilized water more efficiently, and thus produced more grain in dry years when grown under conservation tillage. Conn (1987), however, found that weeds were more prevalent when barley was grown under conservation rather than intensive tillage.

Studies that have examined changes in soil physical properties under long term tillage and crop residue management practices are rare, and even more so in the subarctic. Anken et al. (2004) found that tillage did not affect soil bulk density 14 years after establishing tillage treatments in Switzerland. Arshad et al. (1999) found no change in soil bulk density, but did find enhanced aggregate stability with 12 years of no tillage versus conventional tillage in northern British Columbia. Mahboubi et al. (1993) observed an increase in soil bulk density, penetration resistance, and aggregation with 28 years of no tillage versus conventional tillage in Ohio. Hill (1990) also found an increase in soil density and strength with 12 years of no tillage versus conventional tillage in Maryland. In the subarctic, Sharratt (1996) found that a silt loam was more stable and wetter at the time of sowing in spring with 7 years of no tillage compared with intensive tillage. There are few, if any additional studies that have examined changes in soil properties in response to long term tillage and residue management in the subarctic. Therefore, the intent of this study was to document the impact of 20 years of tillage and residue management on a broad range on soil physical properties that govern wind erosion processes in subarctic Alaska.

2. Materials and methods

Long term tillage and crop residue management practices were established at the University of Alaska-Fairbanks Agriculture and Forestry Experiment Station located near Delta Junction, Alaska (63°N, 145°W). This region has a mean annual air temperature of −2.5 °C and precipitation of 300 mm. The research site was cleared of black spruce (*Picea mariana* (Mill.) B.S.P.) and moss (*Pleurozium schreberi* (Brid.) Mitt., *Sphagnum* spp.) vegetation in 1979 and cropped to barley (*Hordeum vulgare* L.) beginning in 1982. Tillage and straw management treatments were initiated in the spring of 1983 and all treatments were established by autumn 1983. The experimental design was a strip plot with three replications. Tillage was the main treatment and consisted of: (1) intensive tillage in which the soil (coarse-silty over sandy or sandy-skeletal, mixed, non-acid Aquic Eutrocryept) was disked after harvest in the autumn and in the spring prior to sowing, (2) conservation tillage in which the soil was disked prior to sowing in the spring, (3) conservation tillage in which the soil was chisel plowed after harvest in the autumn, and (4) no tillage. Tillage operations were performed to a depth of 0.1 m. Straw management was the secondary treatment, but only two of the three treatments were examined in this study due to little influence of straw management on soil properties in a previous study (Sharratt, 1996). The two straw treatments examined were: (1) stubble and loose straw retained on the soil surface and (2) removal of stubble and loose straw from the soil surface by cutting the stubble and then raking and baling residue after harvest. Main plots were 23 m × 120 m and split to accommodate straw treatments.

Immediately following spring tillage in mid-May each year, N fertilizer was applied at 95 kg ha^{-1} and barley was sown at 100 kg ha^{-1}. Broadleaf weeds were controlled by using a post-emergence herbicide. Barley was harvested in late August or early September using a combine equipped with a straw spreader.

2.1. Soil properties

Soil physical properties were examined after sowing but prior to tillering of barley in May 2004. Soils are most susceptible to wind erosion at this time of year due to the preponderance of strong southerly winds, dry soils as a result of little precipitation during spring, and lack of soil surface cover or roughness as a result of tillage and sowing operations. Soil properties were assessed between crop rows and wheel tracks at 10 locations within each plot. The mineral soil surface of the no tillage treatment was masked by an organic layer (a viable canopy of moss underlain by a 10 mm thick mat of fibric and hemic materials). Therefore, special care was taken to remove the organic layer overlying the mineral soil prior to measuring penetration resistance, shear strength, soil water content, bulk density, and aggregate size distribution in the no tillage treatment.

Penetration resistance was measured using a hand-held, recording penetrometer with a 30° cone. The penetrometer was inserted into the soil at a rate of 20 mm s^{-1} and resistance (resolution of 35 kPa) was recorded when the base of the cone was at the same elevation as the soil surface and at a depth of 25, 50, 75, and 100 mm. Shear strength of the soil surface was measured using a torsional vane shear device. The device recorded the maximum force (resolution of about 1 kPa) to produce slippage as a torsional force was applied to the head of the vane. The head of the vane was 48 mm in diameter and comprised of 16 blades, half of which were 7.5 mm wide and half 17 mm wide. Each blade was 5 mm high. The vane shear device was pressed into the soil surface to the depth of the vane. Soil water content was measured by Time Domain Reflectometry (TDR) within 200 mm and concurrently with penetration resistance and shear strength. The waveguides of the TDR were 100 mm in length and inserted at both 30° and 90° to the soil surface (30° angle achieved using a jig) to facilitate measuring volumetric water content in the upper 0.05 and 0.10 m of the soil profile, respectively. Soil bulk density was determined by extracting soil core samples from the 0–0.05 m depth using stainless steel tubing (0.07 m diameter and 0.05 m long). The tubing was inserted into the soil until the upper edge of the tube was level with the soil surface; the tubing was then extracted by hand from the soil. The soil was trimmed level with the upper and lower edges of the tube. The core samples were then placed in an oven and allowed to dry at 105 °C prior to measuring the soil dry weight (for bulk density). Aggregate size distribution was determined by sieving. Soil samples (about 1 kg) were taken from the upper 20 mm of the soil profile using a flat-bottom shovel. The sample was placed on a plastic tray and air dried. Straw lying on the surface of the sample was removed prior to sieving. The sample was sieved through a nest of sieves having nominal openings of 12.5, 6.4, 2.0, 0.85, 0.42, 0.25, 0.125, and 0.053 mm. The 12.5, 6.4, and 2.0 mm size fractions were obtained by gently hand sieving the sample. The finer size fractions were obtained using a modified sieve shaker (Gilson model SS-45A); the shaker allowed three-dimensional sieving and was operated at a frequency of 2 Hz for 60 s using a 12-V dc power source. Approximately 0.2 kg of the sample was sieved at a time to prevent overloading screens. Preliminary sieving of the field soil ensured that the duration and mass of soil sieved was sufficient so as to retain no more than about 1% of the mass smaller than the nominal opening (ASTM, 2003). Periodic assessments indicated that mass retention averaged 2.5% for this study. Aggregate mean diameter, or size at which 50% of the soil mass passed through a sieve, was determined based upon a log-normal and Weibull distribution of soil aggregates (Zobeck et al., 2003).

Surface random roughness and percent crop residue cover were determined using a microrelief pin meter. The meter consisted of a rigid frame with 40 pin guides spaced 25 mm apart. Pins moved vertically through the pin guides. Once the pins came to rest on the surface, the height of the top of each pin (to within 1 mm) was determined from a scale mounted on the frame. Random roughness was calculated as the standard deviation of height readings, after the readings were corrected for slope, using the procedure of Currence and Lovely (1970). Residue cover was determined by counting the number of pins that completely touched a piece of plant residue (Shelton and Dickey, 1992).

Crop residue biomass was assessed by separately collecting prostrate and standing residue on the soil surface from an area of 0.25 m^2. Standing residue included any residue element anchored to the soil surface and only that portion protruding above the surface. For the purpose of this study, crop residue consisted of that derived from barley, bluejoint reedgrass (*Calamagrostis canadensis* (Michx) Nutt.), sheperd's-purse (*Capsella bursa-pastoris* (L.) Medic.), mare's-tail (*Hippuris vulgaris* L.), and rough cinquefoil (*Potentilla norvegica* L.). The latter four weed species were prevalent only in no tillage plots. The residue was dried at 40 °C and weighed.

2.2. Statistical analysis

Analysis of variance was used to test for differences among treatments. Experimental data were analyzed using a strip plot design. In the event that significant F-values ($P \leq 0.05$) were found, differences among treatments were separated using Least Significant Difference (LSD).

3. Results and discussion

The soil physical state examined after sowing barley in the spring of 2004 was likely impacted by the unusually wet spring of 2004 and the failure to harvest a crop in 2002 and 2003. Precipitation during May 2004 was 37 mm greater than the 30-year normal of 20 mm. One precipitation event (3.1 mm on May 19) occurred within hours after sowing, resulting in the formation of a thin (1 mm) crust, while five additional events (1.5 mm on May 25, 3.9 mm on May 26, 4.8 mm on May 27, 5.1 mm on May 29, and 1.6 mm on May 31) occurred during the course of this experiment. While soils are normally dry and unconsolidated after sowing in interior Alaska, these events likely affected the susceptibility of this soil to wind erosion due to changes in soil physical properties associated with wetting and drying as well as raindrop impact after sowing.

Barley was not harvested in 2002 and 2003 due to pest infestations. In 2002, the experimental plots were sown to barley, but the grain was consumed by sandhill cranes and Canada geese prior to harvest. Sufficient straw remained after foraging by the cranes and geese, however, such that straw treatments could be maintained in 2002. In 2003, severe weed infestations in no tillage necessitated applying herbicides throughout the spring and summer. As a consequence, barley was not grown and straw treatments were not applied on any of the experimental plots that year. Tillage treatments, however, were applied to the plots in the spring and autumn of 2003. These events resulted in the addition of little barley residue to the soil as reflected in low residue biomass and cover in spring 2004 (Table 1). Indeed, in years without a crop failure, we expected higher residue biomass and cover for the conventional and minimum tillage treatments at the time of sowing in spring. For example, residue biomass following harvest of barley varied from 500 to 3500 kg ha^{-1} based upon the same range in grain yield averaged across 4 years at the experimental site (Sharratt, 1998) and an approximate 1:1 straw–grain ratio for barley in interior Alaska (Sharratt and Cochran, 1992). Residue biomass diminishes with time as a result of overwinter processes as well as tillage and sowing operations (Papendick and Moldenhauer, 1995). Assuming a reduction in surface biomass of 30% due to overwinter processes, 40% by disking, 30% by chiseling, and 20% as a result of sowing, the following are ranges in residue biomass expected after sowing in the spring: 100–700 kg ha^{-1} for intensive tillage, 200–1350 kg ha^{-1} for autumn chisel, 170–1200 kg ha^{-1} for spring disk, and 300–1950 kg ha^{-1} for no tillage. Estimates of crop residue cover based upon residue biomass (Papendick and Moldenhauer, 1995) suggests a range in residue cover of 5–30% for intensive tillage, 10–50% for autumn chisel and spring disk, and 20–70% for no tillage. In the spring of 2004, no tillage resulted in greater crop residue biomass and cover as compared with other tillage treatments (Table 1). In fact, no tillage resulted in nearly 100% residue cover despite the lack of any crop to harvest the previous year. Residue cover on all other tillage treatments ranged from 2 to 4%. The high percentage of residue cover in no tillage appears anomalous in comparison to the estimates based upon biomass (Papendick and Moldenhauer, 1995), which was 50% cover for 1275 kg ha^{-1} of prostrate residue in no tillage (Table 1). Crop residue biomass for the no tillage plots was derived from volunteer barley, bluejoint reedgrass, sheperd's-purse, mare's-tail, and rough cinquefoil. Although not considered in the biomass assessment, moss also covered the surface and was therefore considered in assessing soil cover. Thus, although standing and prostrate crop residue was sufficient to minimize wind erosion, greater protection from the forces of wind was afforded by the moss. Retaining straw on the soil surface resulted in greater biomass and cover (Table 1). The response in residue biomass and cover to straw management, however, was dependent on tillage as demonstrated by a significant ($P < 0.05$) straw × tillage interaction.

Table 1
Surface residue cover and biomass after sowing spring barley in a soil that had been subjected to 20 years of tillage and residue management practices in interior Alaska

Tillage/residue	Residue cover (%)	Residue biomass (kg ha^{-1})		
		Prostrate	Standing	Total
Intensive	2.2	31	12	43
Autumn chisel	4.1	104	50	154
Spring disk	3.0	59	32	91
No tillage	99.8	1274	1490	2764
LSD (0.05)	0.4	270	96	320
Residue retained	27.6	450	451	900
Residue removed	26.8	285	341	626
LSD (0.05)	0.6	ns	68	227

ns: not significant.

This study was initiated 20 years after the establishment of treatments in 1983 and 14 years after a previous study (Sharratt, 1996). Many similarities with the previous study were still evident with an additional 14

Table 2
Water content (0–50 mm depth), surface shear stress, bulk density (0–50 mm depth), and surface random roughness of a soil after sowing spring barley

Tillage	Water content ($m^3 m^{-3}$)	Shear stress (kPa)	Bulk density ($Mg m^{-3}$)	Random roughness (mm)
Intensive	0.06	10	0.80	6.0
Autumn chisel	0.05	12	0.77	11.7
Spring disk	0.06	16	0.67	9.5
No tillage	0.23	138	0.71	5.4
LSD (0.05)	0.05	7	ns	1.1

ns: not significant. Soil had been subjected to 20 years of tillage and residue management practices in Alaska.

years of applying tillage and residue treatments. For example, tillage but not residue management influenced water content in the upper 50 mm of the soil profile (Table 2). No tillage resulted in wetter soil, even to a depth of 100 mm in this study. Indeed, soil water content in the upper 100 mm of the profile averaged 0.35 $m^3 m^{-3}$ in no tillage, 0.14 $m^3 m^{-3}$ for spring disk, 0.12 $m^3 m^{-3}$ for intensive tillage, and 0.11 $m^3 m^{-3}$ for autumn chisel (LSD = 0.05 $m^3 m^{-3}$). Bulk density changed little during 14 years and continued to range from 0.65 to 0.80 $Mg m^{-3}$. Penetration resistance and percent non-erodible aggregates changed little during the past 14 years. Penetration resistance was higher to a depth of at least 50 mm in no tillage as compared with other tillage treatments (Fig. 1). The apparent anomaly that tillage effectively altered penetration resistance and not bulk density has also been observed for a sandy loam cropped to spring barley in the United Kingdom (Braim et al., 1992). Percent non-erodible aggregates after sowing ranged from about 50 to 85% across treatments. No tillage had a higher proportion of non-erodible aggregates as compared with other tillage treatments (Table 3). Although our results indicate that no tillage promoted the formation of non-erodible aggregates, none of the tillage practices posed a serious risk for wind erosion because of a high percentage (>40%) of non-erodible aggregates (Campbell et al., 1993).

Table 3
Non-erodible aggregates (>0.85 mm) and aggregate mean diameter of a soil after 20 consecutive years of tillage practices in Alaska

Tillage	Non-erodible aggregates (%)	Aggregate mean diameter (mm)	
		Log-normal	Weibull
Intensive	49.6	1.7	1.6
Autumn chisel	51.6	3.0	3.0
Spring disk	58.0	2.7	2.5
No tillage	87.6	7559	19207
LSD (0.05)	6.7	2426	5317

Aggregate mean diameter was determined after sowing spring barley from log-normal and Weibull distributions.

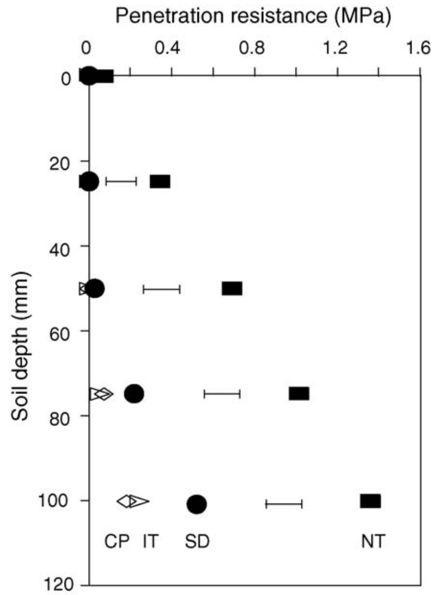

Fig. 1. Penetration resistance to a depth of 100 mm in a soil profile after sowing barley in the spring. Soil had been subjected to 20 years of no tillage (NT), spring disking (SD), autumn chisel plowing (CP), and intensive tillage (IT) in interior Alaska. Horizontal bars indicate LSD at $P = 0.05$.

A notable accumulation of organic material (viable moss underlain by fibric and hemic materials 10 mm thick) was observed on the soil surface of no tillage treatments, but not in other tillage treatments where the soil had been disked or chiseled. The organic layer overlying the mineral soil surface in the no tillage treatments was not apparent in 1990 (Sharratt, 1996). In 1986, 3 years after establishing these tillage and straw treatments, Sparrow and Cochran (1988) noted a buildup of soil organic matter in no tillage compared to other tillage treatments. They surmised that such an accumulation of organic matter with time would depress temperature and increase wetness of soil. Indeed, the accumulation of organic material on the soil surface over the past 14 years has important ramifications for long term tillage management in the subarctic. Thickening of an organic layer on a mineral soil surface would likely cause gradual cooling of the soil and reduce soil temperature below the threshold required for seed germination or root growth.

Aggregate mean diameter was greater for no tillage than for other tillage practices (Table 3), indicating that no tillage promoted the formation of larger aggregates. Mean diameter of aggregates for the no tillage treatment was large, but not atypical of agricultural soils. Zobeck et al. (2003) reported larger aggregate diameters for Kansas soils, but offered no explanation for the large mean diameters. In this study, a large percentage of the no tillage soil was composed of aggregates >12.5 mm (largest sieve size used in our analysis). Indeed, aggregates >12.5 mm constituted 82% of the no tillage soil, whereas it constituted 29% of the autumn chisel soil, 27% of the spring disk soil, and 22% of the intensive tillage soil. The high percentage of aggregates >12.5 mm in the no tillage treatment greatly influenced aggregate mean diameter since estimates of mean diameter derived from both the log-normal and Weibull distributions were obtained by extrapolating beyond the measured size range. All tillage treatments had aggregate mean diameters of 1.5 mm or more, thus these soils were not prone to wind erosion since particles with diameters >0.84 mm would generally be considered non-erodible by wind (Chepil, 1942). However, any degradation of this subarctic soil, particularly when subjected to intensive tillage, could render this soil susceptible to wind erosion.

Surface torsional shear strength was greater for no tillage than for other tillage treatments (Table 2). High shear strength corresponded to greater penetration resistance measured at the soil surface in no tillage compared to all other treatments. Indeed, penetration resistance at the soil surface was 0.07 MPa in no tillage as compared to 0 MPa in autumn chisel, spring disk, and intensive tillage treatments (LSD = 0.06 MPa). Structural dissimilarities likely contributed to differences in shear strength and penetration resistance among tillage treatments.

Four precipitation events (totaling 13 mm) occurred between the time of sowing and measuring random roughness in the spring. Little degradation of roughness (3%) was expected to occur as a result of raindrop impact based upon the relationship between random roughness and precipitation developed by Zobeck and Onstad (1987). Random roughness was greater for autumn chisel compared to all other tillage treatments (Table 2). This was expected since a chisel plow creates a rougher surface than a disk implement (Gupta et al., 1991). Spring disk resulted in a rougher surface as compared with no tillage and intensive tillage. Cresswell et al. (1991) observed that more intensive tillage resulted in smoother surfaces. Soil roughness is an important factor governing soil loss as a result of wind erosion, but the effectiveness of surface roughness in reducing soil loss can be influenced by surface cover. Indeed, Horning et al. (1998) examined the influence of small grain residue cover and random roughness on soil loss during high wind events. Based upon their data, residue cover and random roughness measured for the various treatments in this study (Tables 1 and 2) indicate a soil loss ratio of 0 for no tillage, 0.44 for autumn chisel, 0.53 for spring disk, and 0.66 for intensive tillage. These soil loss ratios would be indicative of the percent reduction in soil loss achieved by adding roughness and residue cover to a smooth and bare surface. Thus, as compared to a smooth and bare surface, no tillage was estimated to be 100% effective in reducing soil loss while autumn chisel, spring disk, and intensive tillage were estimated to be 56, 47, and 34%, respectively, effective in reducing soil loss during high wind events.

4. Conclusions

Tillage and crop residue management practices resulted in little further change to the physical state (i.e. bulk density, penetration resistance, and aggregation) of the soil between 7 and 20 years of management. No tillage promoted soil physical characteristics that were more stable and less prone to erosion in the subarctic. No tillage, however, did not appear to be sustainable due to a lack of strategies to control weeds (Conn, 1987) and accumulation of organic material on the soil surface. The accumulation of organic material on the soil surface over the past 14 years could have important implications for insulating and cooling soils in the subarctic. Thus, some tillage may be required to prevent accumulation of organic material on the soil surface and to control weeds. Although managing crop residue influenced residue cover and biomass after sowing in the spring, retaining or removing crop residue on the soil surface after harvest did not greatly affect soil physical properties. Autumn chisel and spring disk appear to be viable minimum tillage options. Autumn chisel and spring disk promoted greater roughness, aggregation, and residue cover compared with intensive tillage, thereby minimizing the risks of wind erosion.

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